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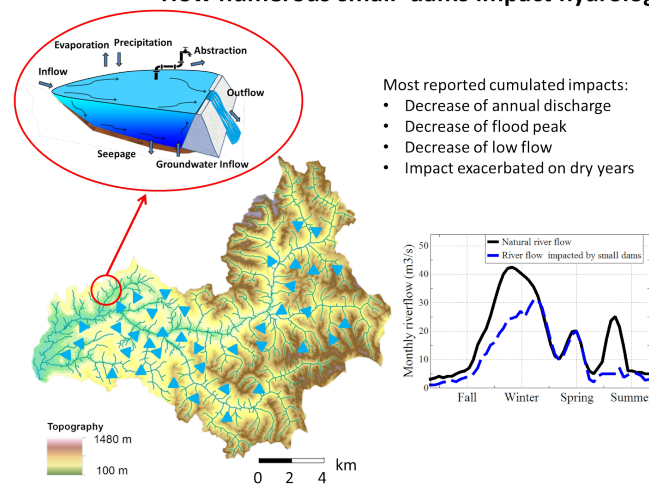
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The cumulative impacts of small reservoirs on hydrology: a review

How numerous small dams impact hydrology ?



Most reported cumulated impacts:

- Decrease of annual discharge
- Decrease of flood peak
- Decrease of low flow
- Impact exacerbated on dry years

Highlights

- The number of small dams is still increasing and is approaching 39 dams per square kilometre
- Small dams lead to a decrease in annual stream discharge of $13\% \pm 8\%$
- Cumulative impacts cannot be estimated using simple indicators
- Cumulative impacts are difficult to estimate and are most often quantified from modelling
- The lack of information on small reservoir characteristics is a real shortcoming for properly estimating their cumulative impacts

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The cumulative impacts of small reservoirs on hydrology: a review

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Abstract

The number of small reservoirs has increased due to their reduced cost, the availability of many favourable locations, and their easy access due to proximity. The cumulative impacts of such small reservoirs are not easy to estimate, even when solely considering hydrology, which is partially due to the difficulty in collecting data on the functioning of such reservoirs. However, there is evidence indicating that the cumulative impacts of such reservoirs are significant.

The aim of this article is to present a review of the studies that address the cumulative impacts of small reservoirs on hydrology, focusing on the methodology and on the way in which these impacts are assessed.

Most of the studies addressing the hydrological cumulative impacts focused on the annual stream discharge, with decreases ranging from 0.2% to 36% with a mean value of 13.4% \pm 8% over approximately 30 references. However, it is shown that similar densities of small reservoirs can lead to different impacts on stream discharge in different regions. This result is probably due to the hydro-climatic conditions and makes defining simple indicators to provide a first guess of the cumulative impacts difficult. The impacts also vary in time, with a more intense reduction in the river discharge during the dry years than during the wet years. This finding is certainly an important point to take into consideration in the context of climate change.

Two methods are mostly used to estimate cumulative impacts: i) exclusively data-based methods and ii) models. The assumptions, interests and shortcomings of these methods are presented. Scientific tracks are proposed to address the four main shortcomings, namely the estimation of the associated uncertainties, the lack of knowledge on reservoir characteristics and water abstraction and the accuracy of the impact indicators.

1. Introduction

Large reservoirs have strong impacts on hydrology at regional to global scales. Indeed, it was estimated that such large reservoirs have led to a global runoff decrease of approximately 2% (Biemans et al., 2011), to a sea level decrease of approximately 30 mm (Chao et al., 2008), and that they store a volume equivalent to approximately 10% of the natural annual soil storage capacity at the global scale (Zhou et al., 2016). However, these studies did not consider the impacts of smaller reservoirs on hydrology. Downing (2010) found that small ponds and lakes (smaller than 0.1km^2) cover a larger area and are more numerous than large reservoirs and that approximately 10% of them are constructed reservoirs.

When considered individually, each reservoir may modify its local and remote environment. The cumulative impacts of many reservoirs in a catchment are the modifications induced by a set of reservoirs (or reservoir network) taken as a whole. The cumulative impacts are not necessarily the sum of individual modifications because reservoirs may be inter-dependent, such as cascading reservoirs along a stream course. Cumulative impacts are not the simple addition of individual impacts: they can develop via an additive or incremental process, a supra-additive process (where the cumulative effect is greater than the sum of the individual effects) or an infra-additive process (where the cumulative effect is less than the sum of the individual effects). The total impact is therefore equal to the sum of the impacts of the developments and to interaction effects. Indeed, addressing the cumulative impacts implies covering different spatial and temporal scales (Canter and Kamath, 1995) and having a reference state (McCold and Saulsbury, 1996). The cumulative impacts of small reservoirs on sediment transport, biochemistry, ecology and greenhouse gas emissions have been studied (Berg et al., 2016; Mbaka and Wanjiru Mwaniki, 2015; Downing, 2010; Poff and Zimmerman, 2010; St. Louis et al., 2000), as have the impacts of such reservoirs on hydrology (Nathan and Lowe, 2012; Fowler et al., 2015). The reported impacts are generally strong but present a large variation.

Estimating the cumulative impacts of systems of small reservoirs on a given basin has become an issue as their number increases (for instance, a 3% increase per year in the US (Berg et al., 2016)). This trend may persist because these systems are often considered to be a technique to

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29 adapt to climate change (van der Zaag and Gupta, 2008). Indeed, small reservoirs are mainly
30 used to store water during the wet season to support water use during the dry season, particularly
31 for irrigation and livestock in rural areas (Wisser et al., 2010; Nathan and Lowe, 2012); to store
32 water during storms to prevent flooding; or to store sediments in check dams to reduce erosion
33 and muddy flood risks. Because the part of the global population that will experience water
34 scarcity is projected to increase with climate change and because the intensity of storm events is
35 also projected to simultaneously increase (Pachauri et al., 2014), there is increasing pressure to
36 construct small reservoirs (van der Zaag and Gupta, 2008; Thomas et al., 2011).

37 However, an uncontrolled development of such small reservoirs may increase the water re-
38 source problem in both quantitative and qualitative ways. Thus, water managers are seeking some
39 indicators that would help to determine optimal networks of small reservoirs in terms of storage
40 capacities and in terms of locations and management. Consequently, in France, the Ministry of
41 the Environment requested a joint scientific assessment to collect useful information/knowledge
42 and tools to provide local stakeholders with such indicators and methods to assess the cumulative
43 impacts of small reservoirs. This request led to a review covering biochemistry, ecology, hydrology
44 and hydromorphology (Carluer et al., 2016). In this paper, a full review of the cumulative
45 impacts of small reservoirs on hydrology is presented because the hydrological impact will affect
46 the other impacts. Although there is no accepted definition of small reservoirs, it is commonly
47 accepted that the storage capacities of such reservoirs are below 1 *million m³*, as stated by Ayalew
48 et al. (2017) and Thomas et al. (2011). This review does not extend to the very small reservoirs
49 of few hundreds of *m³* that can be used for water harvesting (Lasage and Verburg, 2015).

50 First, a synthesis of the quantification of the impacts at the basin scale is presented, and the
51 ability of some conventional descriptors to be used as indicators is studied. Then, the various
52 ways in which small reservoirs can impact the water cycle are presented, along with the methods
53 that are used in the literature to estimate the cumulative impacts of such numerous and not always
54 well-known structures. These results are then discussed, addressing the uncertainties, long-term
55 trends, and impacts on other biochemical, ecological and social components.

56 **2. Evidence of the impacts of small reservoirs on hydrology**

57 From the literature review, the cumulative impacts of small reservoirs on hydrology are most
58 often estimated from the annual discharge, low flows and floods. There is a general consensus

59 that sets of small reservoirs lead to a reduction in the flood peaks (Frickel, 1972; Galea et al.,
 60 2005; Nathan and Lowe, 2012; Thompson, 2012; Ayalew et al., 2017) of up to 45%, particularly
 61 since some reservoirs are constructed as stormwater retention ponds (Fennessey et al., 2001;
 62 Del Giudice et al., 2014). However, over-topping flooding or dam failure can result in large
 63 floods (Ayalew et al., 2017), which may lead to casualties including death (Tingey-Holyoak,
 64 2014). Such failures can be more frequent for small dams than for larger dams due to the lack of
 65 adapted policies, which may lead to a lack of maintenance and a tendency to store excess water
 66 to secure production (Pisaniello, 2010; Camnasio and Becciu, 2011; Tingey-Holyoak, 2014).

67 The low flows are also frequently reported to decrease when a set of small reservoirs is
 68 present in a basin (Neal et al., 2000; O'Connor, 2001; Hughes and Mantel, 2010; Nathan and
 69 Lowe, 2012; Thompson, 2012) with a large spread (0.3 to 60%), although the water stored can
 70 occasionally be used to sustain a low flow (Thomas et al., 2011). The majority of studies have
 71 focused on the annual stream discharge, reporting a decrease in the mean annual discharge that
 72 ranges from 0.2% (Hughes and Mantel, 2010) to 36% (Meigh, 1995). On average, in approxi-
 73 mately 30 references, the decrease in the mean annual discharge reaches 13.4% \pm 8% (Figure 1
 74 and Appendix Table A.1).

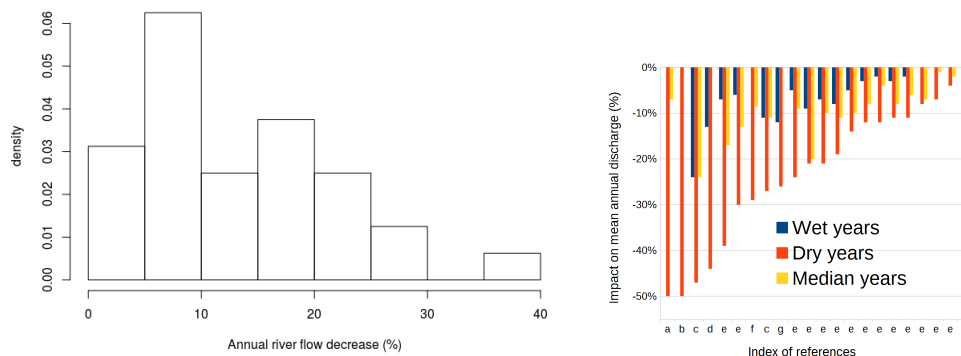


Figure 1: Left: Distribution of the estimated annual stream discharge decrease attributed to reservoir networks. The distribution is established based on 20 values. Right: Impact on the annual discharge estimated during wet, median and dry years. Each bar corresponds to a different catchment. The estimations are from the following references: a: Gutteridge-Haskins-Davey (1987), b: Ockenden and Kotwicki (1982), c: Dubreuil and Girard (1973), d: Cresswell (1991), e: Teoh (2003), f: Habets et al. (2014), and g: Kennon (1966).

75 The right part of Figure 1 shows that the impacts on annual flows are not constant from year
 76 to year but tend to be lower during the wet years and two times greater than the median impact

77 in the driest years. This result is very important because it indicates that even without changing
78 the small reservoir network, its impacts will change in the context of climate change: it may
79 decrease in areas that will become wetter but may increase in areas that will become drier.

80 One key issue in estimating the cumulative impacts is understanding how such impacts are
81 related to the reservoir network, i.e., the level at which the basin is equipped with small dams
82 to avoid over-equipping the basin, with consequences in terms of economy and ecology. Having
83 a single indicator or a set of indicators capable of estimating the cumulative impacts of small
84 reservoirs on the mean annual discharge would be helpful to most water management agencies.
85 Based on the estimated values collected in the literature, a preliminary analysis was performed
86 to determine whether some easy-to-access properties of the reservoir network could be used as
87 indicators. For this purpose, we collected the main characteristics of the basins and of their small
88 reservoir network from the available studies and attempted to connect them to the impacts on the
89 mean annual discharge. We used the reservoir's density, expressed as the number of reservoirs
90 per square kilometre or as the volume stored per square kilometre, and the mean precipitation
91 or the mean discharge in the basin. The results presented in Figure 2 show that none of these
92 characteristics are able to be used as indicators for such contrasted basins as the ones found in
93 the literature. Indeed, within a narrow range of specific discharge or precipitation, the decrease
94 of the annual discharge varies a lot and can not be correlated to the density of reservoir network.

95 A more regional-scale view could be useful to attempt to disentangle different types of cli-
96 mate or use. However, according to the sample of available studies, only a continental-scale anal-
97 ysis was possible. It appears from these figures that the general characteristics present a wider
98 spread between continents than within a given continent, even if the results are from different
99 studies. For instance, the specific discharge is low in Australia, the density is low in Africa, and
100 the storage volume tends to be important in America. However, even within a continent, these
101 characteristics are not sufficiently well linked to the impacts to be reliably used as indicators.

102 This result occurs because the cumulative impacts of reservoir networks rely on a large num-
103 ber of factors: the hydrological processes occurring in each reservoir, the water management
104 (water abstraction rate and timing, water uptakes from and releases to the river), the reservoir
105 characteristics, the reservoir network geometry, and the connectivity of each reservoir to the
106 stream drainage network. These points are detailed below.

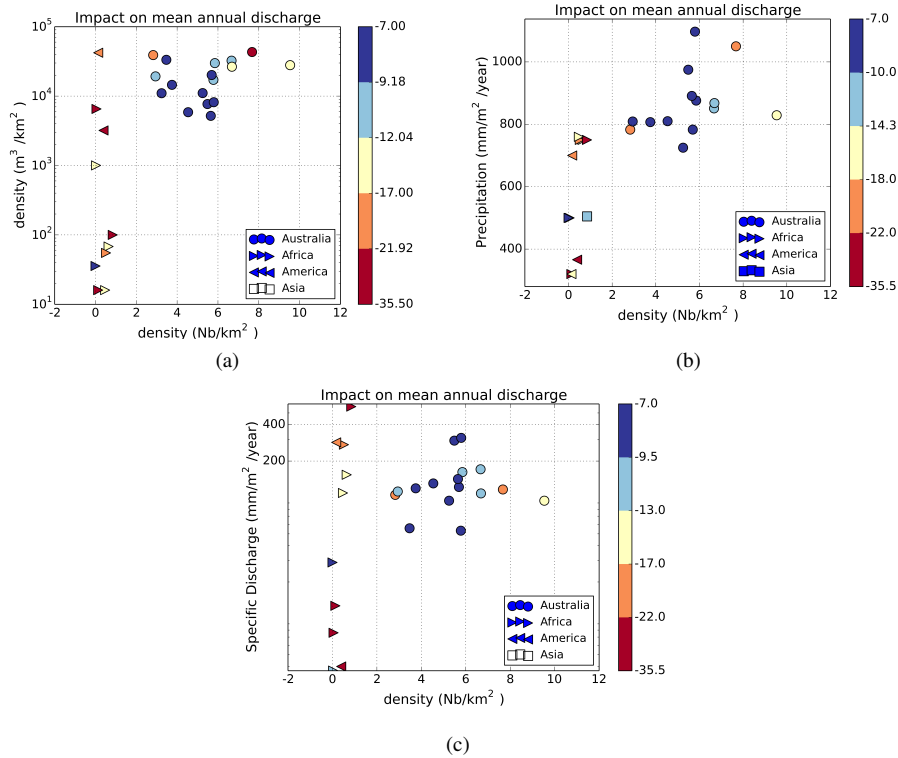


Figure 2: Cumulative impacts of the small reservoirs on the mean annual discharge (colour scale on the right), estimated from studies reported in Appendix Table A.1, as a function of possible indicators: reservoir density expressed as the number of dams per square kilometre and as storage capacity in cubic meter per square kilometre, annual precipitation expressed in $mm/m^2/year$, or specific discharge expressed in $mm/m^2/year$. Each point represents a catchment, and the symbol corresponds to different regions: Africa, America, Asia, and Australia.

107 3. How do small reservoirs impact hydrology?

108 Small reservoirs have an impact on hydrology because they affect the natural water cycle that
 109 would occur without reservoirs. To understand how networks of small reservoirs impact river
 110 flow at the basin scale, it is necessary to understand the functioning of a single reservoir, how it
 111 can have an impact on the river flow and why the impact varies in time and from one reservoir to
 112 another.

113 3.1. Water balance of a small reservoir

114 Figure 3 presents the various terms of the water balance of the reservoir. From a general
 115 perspective, the reservoir water balance can be expressed by the following equation:

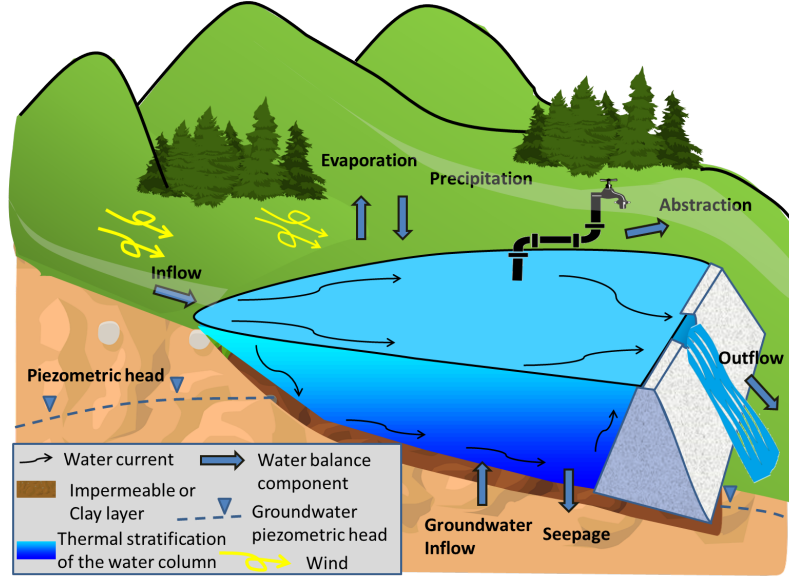


Figure 3: Water balance of a small reservoir and its main drivers. The components of the water balance are indicated by large arrows: inputs can be inflows, such as upstream runoff, lateral surface runoff, and direct precipitation; outputs can be outflows, abstraction, seepage and evaporation.

$$\frac{dV}{dt} = Q_{in} + P + GW_{in} - Q_{out} - E - S - Q_{abs} \quad (1)$$

116 Here, dV is the water volume variation [m^3] over the period dt [s], Q_{in} is the stream inflow
 117 to the reservoir [m^3/s], Q_{out} is the outflow from the reservoir [m^3/s], E is the evaporation rate
 118 [m^3/s], P is the precipitation rate [m^3/s], S is the seepage rate [m^3/s], GW_{in} is the groundwater
 119 inflow [m^3/s] and Q_{abs} is the water abstraction [m^3/s].

120 Inflow can have 4 sources: i) the upstream flow, which depends on the way in which the
 121 reservoir is connected to the river (Section 3.3); ii) the surface runoff from the area directly
 122 drained by the reservoir along its bank; iii) the intercepted precipitation; and iv) a groundwater
 123 inflow, although none was reported in the literature review.

124 Outflux includes outflow (downstream flow) and water abstraction, as well as evaporation and
 125 seepage losses from the reservoir. Outflow is defined as the downstream flow due to reservoir
 126 release. Abstraction corresponds to the water uptake, often by pumping, for human use (irriga-
 127 tion, livestock watering, and so forth). Seepage flow may occur as water infiltration through the
 128 reservoir bed or through or below the dam.

129 All these fluxes can vary considerably from one reservoir to another. For instance, abstraction

130 can be the main output, especially for farm reservoirs. However, it can also be null, such as in
131 storm water or check dam reservoirs. Section 6.3 discusses how abstraction can be estimated at
132 the basin scale.

133 Water losses are present for every type of reservoir, but with a large spread of intensity,
134 ranging from the main outflux to negligible ones. The next section focuses on these losses and
135 on how they can be estimated.

136 *3.2. Losses from small reservoirs*

137 *3.2.1. Seepage*

138 Seepage (also called percolation flux) may be particularly important to consider for small
139 reservoirs because most of these reservoirs are built with earthen dams. The seepage rate depends
140 on the hydraulic head gradient between the reservoir and the underlying aquifer (or unsaturated
141 zone) or dam wall, as well as on the hydraulic conductivities of the aquifer and reservoir bed
142 material.

143 Although seepage is a loss at the reservoir scale, the water is not lost and is mostly diverted.
144 Indeed, infiltration tanks, encountered especially in Asia, are built to favour infiltration through
145 the reservoir bed to increase the groundwater recharge. In this way, a larger part of the monsoon
146 flow is stored in the groundwater while avoiding the evaporation loss from reservoirs during the
147 dry season (Glendenning et al., 2012). However, when dams are intended to store water over
148 the long term, seepage is considered as a loss. In such cases, impervious layers of clay or ge-
149 omembrane (Alonso et al., 1990; Yiasoumi and Wales, 2004) are used to reduce seepage, but
150 their efficiency decreases with age. Thus, irrespective of the intended function of the reservoir,
151 it is rather important to estimate the seepage rate from the reservoir because it determines its ef-
152 ficiency for storing water (then, a low seepage rate is expected) or within the groundwater (then,
153 a high seepage rate is expected). In the literature, estimations of the seepage rate were based on
154 water balance approaches constrained by local observations of the precipitation, potential evapo-
155 ration and reservoir's water level (Culler, 1961; Kennon, 1966; Sukhija et al., 1997; Singh et al.,
156 2004; Bouteffeha et al., 2015), as well as on additional observations of the soil moisture and
157 piezometric heads (Shinogi et al., 1998; Antonino et al., 2005; Massuel et al., 2014), environ-
158 mental tracers (Sukhija et al., 1997), or more frequently on modelling approaches (Zammouri
159 and Feki, 2005; Boisson et al., 2014; Jain and Roy, 2017).

160 Figure 4 presents some estimations of the seepage and evaporation losses from the literature

161 under different hydroclimatic contexts and for reservoirs built for various purposes. Most esti-
162 mated seepage values are greater than 5mm/day on average in the studied periods, and thus, the
163 seepage rate appears to be higher than the evaporation rate. However, most of the values found
164 in the literature are from percolation tanks, i.e. from dams built to promote a rapid infiltration
165 of the runoff during the wet season to recharge the water table. For the other types of dams, the
166 estimations can be lower: less than 1mm/day for Culler (1961) in the US and up to 6.2mm/day
167 for Shinogi et al. (1998) over a 6-month period in a basin in Brazil. Fowler et al. (2012, 2015)
168 consider that hillslope dams in Australia are not efficient for storing water if the seepage rate is
169 greater than 5mm/day .

170 When the cumulative impacts are considered, both the seepage rate and the seepage fate are
171 important. In the case of infiltration into the dam wall, the seepage water might flow downstream
172 in the river, and thus, the seepage flux might not be lost at the scale of the river basin. An illustra-
173 tion of such a process was provided by Kennon (1966), who observed that ephemeral rivers have
174 become permanent after the implementation of dams built to prevent erosion (see Section 4.1.1),
175 and by those studies that include groundwater recharge from dam seepage (Ramireddygari et al.,
176 2000; Barber et al., 2009; Smout et al., 2010; Shinde et al., 2010; Perrin et al., 2012). Therefore,
177 seepage fluxes from each reservoir should not be aggregated to estimate the loss at the basin scale
178 and thus for the estimation of the cumulative impacts of small dams on hydrology.

179 3.2.2. *Evaporation*

180 Unlike seepage, evaporation fluxes from each reservoir should be aggregated at the basin
181 scale. The impact of the reservoirs on the evaporation losses is then the difference between the
182 evaporation from the land cover that was present prior to the dams being built and the evap-
183 oration from the reservoirs. Such estimations are not straightforward, particularly because the
184 heat storage of the water body affects the surface energy flux (Assouline et al., 2008; McMa-
185 hon et al., 2013). This storage partly depends on the temperature of the water columns, which
186 is impacted by the depth of the dams (although in opposite ways depending on the references
187 (Girard, 1966; Martínez Alvarez et al., 2007; Magliano et al., 2015) due to the associated change
188 in the free water area); on the water circulation within the reservoir (which is also impacted by
189 the reservoir's management); and on the interaction with the edges, which can be rather close
190 for small reservoirs and that affects the wind velocity and the advection of air humidity (Fig-
191 ure 3). Several methods were used to provide estimations of the evaporation from small reser-

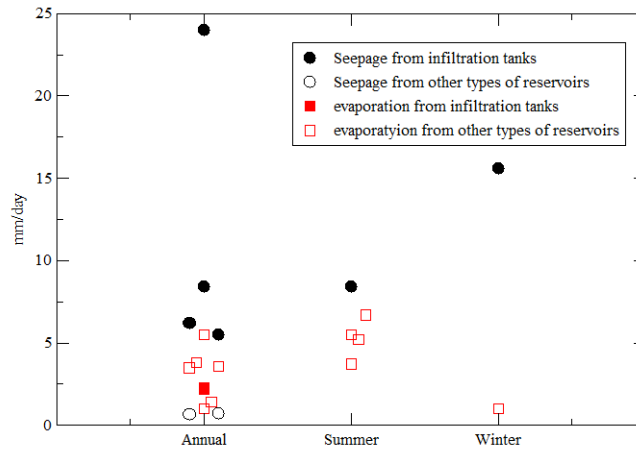


Figure 4: Estimation of the seepage loss and the evaporation flux of small reservoirs on a seasonal to annual basis. Two types of reservoirs are distinguished: infiltration reservoirs and other types of reservoirs. The values are taken from the articles cited in this section.

192 voirs based on observations: energy balance approaches (Anderson, 1954; Culler, 1961; Ken-
 193 non, 1966; Gallego-Elvira et al., 2010), eddy-covariance measurements (Rosenberry et al., 2007;
 194 Tanny et al., 2008; Mengistu and Savage, 2010; Nordbo et al., 2011; McJannet et al., 2013), scin-
 195 tillometers (McJannet et al., 2013; McGloin et al., 2014), and water balance approaches (Girard,
 196 1966; Martínez Alvarez et al., 2007). Figure 4 presents the estimations found in the literature.
 197 The mean annual estimations range from 1.4 to 5.5mm/day, and the reported summer values are
 198 all above 3mm/day.

199 Martínez Alvarez et al. (2007) proposed a relationship between the small reservoir evapora-
 200 tion loss and the Class A pan evaporation that varies according to the reservoir's depth and area
 201 and that varies in time (from 86 to 94%).

202 Several estimations of the small reservoir evaporation loss based on meteorological data were
 203 proposed (de Bruin, 1978; Martínez Alvarez et al., 2007; McJannet et al., 2013; McMahon et al.,
 204 2013; Morton, 1983). Benzaghta and Mohamad (2009), Martínez Alvarez et al. (2008) and Craig
 205 (2008) found that the evaporation losses from reservoirs can be very important at the regional
 206 scale and have an important economic impact.

207 Several techniques might help reduce evaporation from reservoirs: casual chemical treatment

208 to modify the albedo or form a monolayer film, completely or partially covering the reservoirs,
209 managing the reservoir edges to reduce wind speed, and optimizing the use of the water in reser-
210 voir networks based on the temperature of the water in the reservoirs (Barnes, 2008; Lund, 2006;
211 Assouline et al., 2011; Martínez-Alvarez and Maestre-Valero, 2015; Gallego-Elvira et al., 2011;
212 Carvajal et al., 2014; Reca et al., 2015). However, such techniques are not yet widely used and
213 are not considered in the existing cumulative impact studies.

214 3.3. Connection to the stream

215 By itself, the connection of the reservoir to the stream is key to understanding the impacts
216 of the reservoir on the river flow. Indeed, this connection will impact both the inflow and the
217 outflow. Small reservoirs can collect all the upstream flow (Figure 5-a for a hillslope reservoir
218 or dam situated on the stream with no minimum flow) or only a part of the flow (reservoir
219 with minimum flow by-pass, Figure 5-b, which allows maintaining a minimum flow, or dam
220 situated in diversion Figure 5-c since in this case, the reservoir can not fill as long as inflow
221 does not exceed some thresholds). In the case that all the upstream flows are collected, the
222 downstream outflow will primarily depend on the level of the spill and on the reservoir water
223 storage. Following “*fill-and-spill*” (Deitch et al., 2013), downstream discharge occurs only when
224 the reservoir is fully filled; conversely, as long as the reservoir has not reached its capacity,
225 downstream discharge is null. Therefore, it is possible to have periods with no downstream flow
226 while upstream flow exists, such as for hillslope reservoirs and check dams. Such reservoirs have
227 strong impacts on the intensity and the duration of low flows. In particular, the resumption of
228 flow in the fall can be significantly delayed. In the case of diversion or a minimum flow bypass
229 reservoir, a downstream flow is ensured when the upstream flow is non-zero. If the reservoir is
230 located in diversion, then the filling period of the reservoir can be managed such that the reservoir
231 may have no impact on the river flow during parts of the year, which may allow preserving
232 the ecological function of the river. This management can also be adapted to the hydrological
233 situation of each year. The reservoirs built mainly to favour groundwater recharge can have
234 all types of connections with the river; however, it appears that most of them are built directly
235 in the river stream, thus collecting all the upstream flows (Shinogi et al., 1998; Siderius et al.,
236 2015). Depending on the respective inflow and abstraction dynamics, cumulative abstraction
237 may exceed the reservoir storage capacity, as illustrated in Figure 5 for example, for which the
238 abstractions from the reservoirs reach 105 to 120% of the maximum storage capacity.

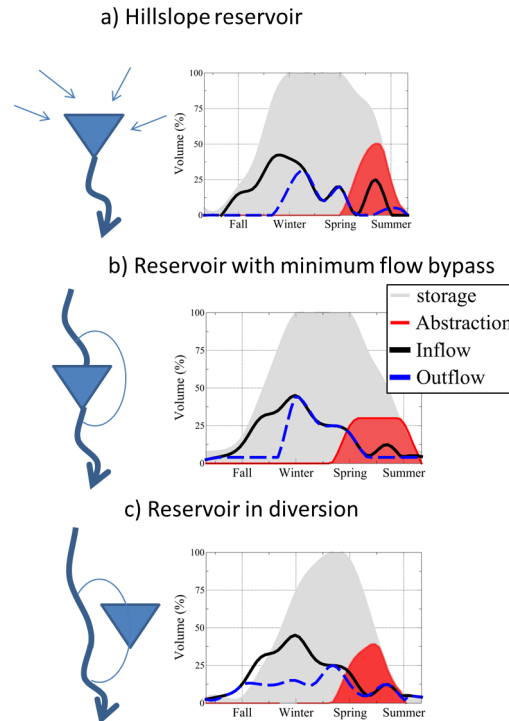


Figure 5: Illustration of 3 different connections between the river and the reservoir and its consequences in terms of river flow. Inflow, outflow and abstraction are accumulated weekly values, whereas storage is a weekly value. They are all expressed as a fraction of the maximum storage. Abstractions in the reservoirs reached 105 to 120% of the maximum storage capacity. a) Hillslope reservoir is managed as a fill and spill, with a weak and irregular inflow. b) The minimum flow bypass ensures that a minimum outflow occurs as long as inflow is present. c) The reservoir in diversion is expected to fill up as soon as the inflow reaches a given minimum flow or depending on management practices.

239 4. Methods to estimate the cumulative impacts of small reservoirs on hydrology

240 Quantifying the cumulative impacts of small reservoirs has been conducted using a variety
 241 of methods, all of them requiring data and observations. Two classes of methods can be distin-
 242 guished: i) the methods exclusively based on the analysis of observed data and ii) the methods
 243 based on hydrological modelling.

244 4.1. Exclusively data-based methods

245 4.1.1. From observation of selected reservoirs to estimation of cumulative impacts

246 This approach was mainly used in early works performed from the 50s to the early 70s in the
 247 US (Kennon, 1966; Culler, 1961; Frickel, 1972) and in Brazil (Dubreuil et al., 1968; Dubreuil
 248 and Girard, 1973; Molle, 1991). In light of these pioneering works, it can be observed that the

249 cumulative impacts on hydrology have been a scientific and water management issue for a long
250 time.

251 Despite some differences in the methodology among these studies, they all aimed at quantify-
252 ing single reservoir hydrologic functioning from the monitoring of a sample of reservoirs. Losses
253 were estimated using a mass balance of the sampled representative reservoirs based at least on
254 the monitoring of the water level, inflows and outflows of the reservoirs. These early studies
255 initially made the assumption that cumulative reservoir impacts were the sum of the impact of
256 each reservoir following an aggregation process. However, the main outcome of these studies
257 was to show that this assumption was not valid. Indeed, Culler (1961) and Kennon (1966) found
258 that the seepage was a significant loss for the sampled reservoirs but contributed to downstream
259 flow. Therefore, interactions between reservoirs and hydrologic compartments, especially the
260 stream, were identified very early as processes to be taken into consideration to reliably estimate
261 the cumulative impacts.

262 4.1.2. *Statistical analyses of the observed discharge*

263 The idea is to connect the detected changes in the statistical properties of river discharge time
264 series with the evolution of the reservoir network within the basin. In doing so, the details of
265 each reservoir functioning are not taken into consideration. To our knowledge, this type of study
266 based solely on observations was only performed by Galea et al. (2005). A study based on a
267 30-year river discharge time series of two French catchments showed no stationarity break in
268 summer, while a break was shown in winter, i.e., during the filling period (Galea et al., 2005).

269 One difficulty of such statistical analyses is discriminating the specific impact of small reser-
270 voirs from those of land use and land cover (LULC) evolution or of climate change (CC). Reser-
271 voir development occurred over decades, a sufficiently long period to be sensitive to LULC mod-
272 ifications (such as agricultural intensification or crop modification) and CC. To overcome this
273 issue, Schreider et al. (2002) compared the observed river flows with simulated ones obtained
274 using the observed atmospheric forcing, but without any explicit representation of the small
275 dams in the models. The IHACRES rainfall-runoff model, a dynamic, lumped parameter model,
276 was used to simulate stream flow with parameters calibrated considering periods before the de-
277 velopment of reservoirs. They found significant decreasing trends in the observed discharge of
278 basins that had a development of farm dam capacity, and they were able to attribute these trends
279 to non-climatic stressors since such trends were not simulated with a reservoir-free basin.

280 *4.1.3. Paired-catchment experiment*

281 A paired-catchment experiment is an approach already used in hydrology for quantifying
282 the impact of LULC changes from a comparative analysis of stream flows monitored in two
283 contrasted catchments (see, for instance, Brown et al. (2005) for a review in forest hydrology).
284 Thompson (2012) is, to our knowledge, the only study using this approach to compare stream
285 flows from two adjacent and similar catchments, one without a reservoir and the second with
286 three small reservoirs. From an 18-month monitoring, annual stream flow was estimated to be
287 lower by 40% in the catchment with 3 reservoirs than in the "no-reservoir" catchment (Thomp-
288 son, 2012). Although the experiment found differences in the specific discharge, the full com-
289 parison of the water balance remained difficult. The main shortcoming of Thompson's approach
290 is that catchment properties (soils, lithology, land cover, topography, and so forth) were spatially
291 heterogeneous over a short distance, making deciphering the stream flow differences difficult.
292 Furthermore, indirect reservoir impacts on land use, such as the cattle grazing around the reser-
293 voir in Thompson's case study, can also modify stream flow. The study would have benefited
294 from following the classic approach used in paired-catchment experiments, implying a calibra-
295 tion period where both catchments are monitored, followed by a period when one of the catch-
296 ments is subjected to land use change (reservoir building) and the other remains as a control.
297 However, building a reservoir network over a large area is generally difficult for practical and
298 financial reasons. Consequently, such an approach has never been utilized to our knowledge.

299 *4.2. Modelling approaches*

300 Modelling is the most widely used approach for studying and quantifying the cumulative
301 impacts of small reservoirs. Although various modelling approaches have been developed, all
302 are based on the coupling of the small reservoir water balance model with a quantitative method
303 to estimate stream inflow into the small reservoirs. Three of the main model components are
304 detailed below: i) the small reservoir water balance model, ii) the quantitative method used to
305 quantify inflow to reservoirs, and iii) the spatial representation of the reservoir network. The
306 inflow quantification method and the spatial representation of the reservoir have to be consistent
307 and are thus intrinsically dependent. A spatially distributed representation of reservoirs requires
308 being able to estimate the spatial distribution of stream flow to estimate the upstream inflow to
309 each reservoir. Conversely, an aggregated estimation of stream flow over a sub-basin or over
310 the full catchment leads to the reservoir network representation being aggregated on the same

311 domain.

312 Most of the reviewed studies focused on assessing the impacts of reservoirs used for irrigation
313 or livestock watering on stream flow. In such cases, the impacts are quantified by comparing the
314 catchment stream flow simulation with and without reservoirs, except for the TEDI model, as
315 we will see in Section 4.2.2. The exceptions to modelling approaches dedicated to stream flow
316 impacts are those aiming at assessing the impacts on groundwater. These approaches mostly
317 focus on infiltration tanks, for which part of the stored volume recharges the aquifer. In such
318 cases, only the impacts on the aquifer due to the loss from the reservoirs are represented, either
319 without simulation of the groundwater (Martín-Rosales et al., 2007; Hughes and Mantel, 2010),
320 with a simplified representation of the aquifer (Smout et al., 2010; Shinde et al., 2010; Perrin
321 et al., 2012), or even more seldom, with a 2-D hydrogeological model (Ramireddygarri et al.,
322 2000; Barber et al., 2009).

323 *4.2.1. Reservoir water balance model*

324 Reservoir water balance models rely on equation (1). Most small reservoir water balance
325 models take into account the evaporation and abstraction, for which temporal estimation is rarely
326 well known and is often an important point (see Section 5.3) (Table 1). When seepage is taken
327 into account, it is considered only as infiltration to groundwater. Ignoring seepage is justified
328 by the small expected rates (Hughes and Mantel, 2010) or by the lack of information on the
329 process (rate, timing, and driving factor Güntner et al. (2004)) and by the fact that seepage flux
330 can contribute to downstream flow. To simulate the reservoir water mass balance, downstream
331 discharge is simulated considering that reservoirs operate with the technique of "fill-and-spill"
332 (Section 3.3, unless a conservation flow is taken into account (Table 1). Reservoir inflow is
333 simulated by different approaches, as presented in the next section.

334 *4.2.2. Reservoir inflow quantification*

335 In most modelling approaches, upstream inflow is provided by a catchment hydrological
336 model simulating the water balance (WB), or the energy and water balance (EWB), in the up-
337 stream catchment and the routing of the flow downstream (Table 1). Existing catchment hy-
338 drological models are used in the modellings, reflecting the diversity of current hydrological
339 models. Such models need atmospheric forcing and some information on the land cover, soil and
340 topography, unless the model parameters are calibrated without any data on the physiographic
341 characteristics. Two models, TEDI and Deitch (Table 1), developed an alternative and pragmatic

342 method based on using observed discharge time series as input to the model. In doing so, the
343 TEDI and Deitch models do not belong to any current modelling approaches. Using observed
344 discharge at available river gauges implies being able to successively i) disentangle the natural
345 flow from the anthropogenic flow and ii) distribute the observed discharge along the reservoir
346 networks. To achieve the first step, Deitch et al. (2013) used historical gauged discharge mea-
347 sured prior to the reservoir pre-development period. The discharge was then spatially distributed
348 according to the drainage area of each reservoir and the spatial distribution of the average annual
349 rainfall. The propagation of stream water was then operated from the most upstream reach to the
350 catchment outlet by considering the water volume intercepted in each reservoir. The cumulative
351 impact of reservoirs is then classically the difference between simulated discharge and the gauged
352 discharge. In TEDI, Nathan et al. (2005) used the observed discharge of the period of interest.
353 The inflow in each reservoir is calculated from the observed catchment discharge assuming a
354 proportionality with the reservoir catchment area. The outflow from every reservoir is transferred
355 directly to the outlet. It is then considered that the obtained cumulative impact corresponds to
356 twice the simulated impact of the reservoir network because the gauge discharge already includes
357 the impacts of existing reservoirs.

358 4.2.3. Reservoir spatial representation

359 How the reservoir network is represented from a spatial perspective varies from one model to
360 another. The spatial representation of the reservoir network can be classified into the following
361 three types (see Figure 6, Table 1).

- 362 • In the *spatially aggregate* approach, all the reservoirs in a catchment (in Table 1, A for
363 aggregation on sub-catchments and A* for aggregation on a grid cell) are represented in
364 the form of a single equivalent, or composite, reservoir.
- 365 • The *statistical representation* constitutes a refinement of the aggregate representation (Fig-
366 ure 6-B). The reservoir network is represented in the model in an aggregated way by group-
367 ing reservoirs into a finite number of classes. Some hydrological connections between
368 several of these classes may be represented (S in Table 1).
- 369 • The *spatially explicit representation* consists of representing every reservoir (Figure 6-C).

Model	spatial representation	time step	Processes included						
			inflow	outflow	evaporation	direct precipitation	seepage	aquifer	abstraction
CRU ⁱ	A	day	WB	CF spill	x	x	x		x
GR4J ^k	A	day	WB						
HYDROMED ^l	A	day	WB	spill	x	x			x
POTYLDR ^j	A	day	WB	CF spill	x	?	x	?	x
ISBA-Rapid ^h	A*	hour	EWB	spill	x				x
SWAT	A ^g , S ⁿ	day	WB	spill	x	x		x	x
TEDI ^a	S	month/day	OBS	spill	x	x			x
WASA ^d	S	day	WB	spill	x		x		x
WaterCAST ^c	S	day	WB	spill	x	x			x
CASCADE ^m	D	day	WB	spill	x		x		x
CHEAT ^b	D	month	OBS	spill	x	x			x
Deitch et al. ^e	D	day	OBS	spill					
PITMAN ^f	A	month	WB	spill	x				x

Table 1: Main processes in reservoir water balance model, as well as temporal and spatial representations of reservoirs in numerical models. Spatial representation can be the following (see Figure 6): A: aggregate representation by catchment (or A* by grid in grid-based models), S: statistical representation, or D: distributed representation. Inflow to the reservoirs can be derived from OBS: observations, WB: water balance, or EWB: energy and water balance. Outflow is computed either based on spill (above a water level or volume in the reservoir) and/or taking into account a conservation flow (CF). ^a: Nathan et al. (2005), ^b: Nathan et al. (2005), ^c: Cetin et al. (2009), ^d: Güntner et al. (2004), ^e: Deitch et al. (2013), ^f: Hughes and Mantel (2010), ^g: Perrin et al. (2012), ^h: (Habets et al., 2014), ⁱ: Tarboton and Schulze (1991), ^j: Ramireddygaru et al. (2000), ^k: Payan et al. (2008), ^l: Ragab et al. (2001), ^m: Shinogi et al. (1998); Jayatilaka et al. (2003), and ⁿ: Zhang et al. (2012)

	Scheme	Principles
catchment		<p>Reservoirs characteristics</p> <ul style="list-style-type: none"> Reservoirs (■) along the stream network (-) Each reservoir has an upslope drainage area (the dashed areas for 2 examples)
A aggregative		<p>Reservoir network represented by an equivalent single reservoir</p> <p>The simulated catchment discharge, Q_{sim}, is the sum of αQ_{gen}, the non-intercepted simulated stream discharge and $Q_{outflow}$, the downstream flow from the equivalent reservoir simulated by the mass balance reservoir model. $(1-\alpha)$ is the catchment areal fraction of the cumulative upslope drainage area of all the reservoirs</p>
S statistical		<p>Reservoir network represented by classes of equivalent reservoirs. Each class corresponds to a given range of reservoir capacity.</p> <p>Q_{gen}, the catchment discharge, is distributed over each reservoir class by simple rules. The outflow from one reservoir class is propagated through the downstream classes by simple rules of cascading.</p>
D Distributed		<p>Each reservoir represented along with its upstream flow ($Q_{inflow,i}$).</p> <p>A single mass balance model, applied to each reservoir, simulated the down stream flow of the reservoir ($Q_{outflow,i}$), which is propagated downstream through the stream network.</p>

Figure 6: Spatial representation of reservoir network in models used to quantify cumulative reservoir hydrologic impacts.

370 *Aggregate representation*

371 In the aggregate representation (Figure 6-A), the characteristics of the equivalent reservoir
372 (capacity and surface area) are obtained by aggregating single reservoir characteristics. The main
373 interest of the aggregate representation is to require only global information about the reservoirs
374 and their characteristics. In fact, the spatial density of reservoirs within a catchment can be large,
375 greater than 10 reservoirs/km² in some cases (Nathan et al., 2005), and an exhaustive inventory
376 of all reservoirs along with their characteristics is out of reach. Rather, a global estimation of
377 reservoirs and their characteristics may be approximated from simple rules of spatial extrapola-
378 tion (cf. Habets et al. (2014)). For instance, to estimate the inflow into the equivalent reservoir,
379 it is necessary to determine the contributive catchment. It can be a fraction of the catchment area
380 (Tarboton and Schulze, 1991; Hughes and Mantel, 2010) that can be estimated from the sum of
381 the drainage area of all reservoirs or depending on the cumulative reservoir area (Habets et al.,
382 2014).

383 The aggregate representation leads to obtaining a simulation of the hydrological cumula-
384 tive impacts of reservoirs at the catchment, grid-cell or sub-catchment outlet but intrinsically
385 does not allow simulating the cumulative impacts along the river network from the head to the
386 outlet, unless the sub-catchments are small, which is often not the case because the size of the
387 sub-catchment is often determined by the availability of river gauges. Furthermore, this represen-
388 tation may not reflect the different responses of the various reservoirs in terms of key processes
389 (evaporation, infiltration, operations, and so forth (Zhang et al., 2012)).

390 *Statistical representation*

391 The statistical representation is a trade-off between the other two representations. It consid-
392 ers that information about the location and characteristics of reservoirs, particularly of small-
393 and medium-sized reservoirs, cannot be exhaustively available. It also relies on the assumption
394 that reservoir connectivity may play a role in the cumulative impacts. The reservoir network
395 is represented by classes of reservoirs determined following reservoir water capacity (Güntner
396 et al., 2004; Nathan et al., 2005; Lowe et al., 2005)) and also reservoir drainage area (Zhang et al.,
397 2012). Each class is represented as a single equivalent reservoir. Güntner et al. (2004) and Zhang
398 et al. (2012) used a coupled sequential and parallel scheme to represent the upstream-downstream
399 connectivity of different water reservoir classes in the catchment.

400 As a main advantage, the statistical representation has to consider the diversity of key reser-

401 voir processes, which can be variable from one reservoir to another but quite homogeneous in
402 reservoirs of similar sizes. In this way, it overcomes one of the main shortcomings of the ag-
403 gregate representation. Evaporation, for example, depends on the water column height and cir-
404 culation within the reservoir, which is expected to depend on reservoir size (cf. Section 3.2).
405 Connectivity to the network –reservoirs and rivers– and operation rules may also be different
406 depending on the reservoir function, which also depends on the reservoir size. Another advan-
407 tage of the statistical representation is being computationally faster than the fully distributed one
408 because fewer reservoir mass balances have to be computed and water transfers between reser-
409 voirs are simplified. The main shortcoming is that it does not obtain distributed simulations of
410 the hydrological impacts of reservoirs; particularly, the cumulative impacts along the full river
411 network cannot be simulated.

412 *Distributed representation*

413 A distributed representation of the reservoir is the only way to explicitly represent the in-
414 teractions between reservoirs by considering the outflow from one reservoir as a contribution to
415 the inflow of the downstream one and the interactions between reservoirs and hydrological com-
416 partments (river, soil, and aquifer) by estimating the impacts of each reservoir on its connected
417 river reach or/and aquifer. Indeed, two dams with similar characteristics may have different im-
418 pacts according to their location along the stream network, mostly because the inflow is not the
419 same. The interest in a spatially explicit representation is in quantifying and understanding the
420 local hydrologic impact at a river reach scale and the cumulative impacts along the river network
421 (Deitch et al., 2013). Quantifying local hydrologic impacts may be particularly relevant to water
422 quality, ecological disturbance or morphogenesis evolution. In a spatially explicit representation,
423 water inflow into every single reservoir as stream discharge and lateral surface runoff has to be
424 known or estimated. To our knowledge, only Shinogi et al. (1998) and Smout et al. (2010) have
425 performed catchment hydrologic modelling to obtain these estimations, with an application to
426 relatively simple case studies characterized by few reservoirs. Other reported case studies using
427 spatially explicit representations used observed-stream-discharge-based models (Nathan et al.,
428 2005; Cetin et al., 2009; Deitch et al., 2013).

429 A spatially explicit representation relies on the availability of exhaustive information about
430 reservoir location, characteristics, water uses and topology, which are rarely available over large
431 areas. This point constitutes a main shortcoming of the approach, as addressed in Section 4.1.1.

432 Furthermore, it can be expected that uncertainties in the local information, added to the uncer-
433 tainty in estimated spatial discharge and individual reservoir water balances, can skew the local
434 simulated impacts, and by propagation, the cumulative impacts. This could alleviate the theoret-
435 ical interest in the spatially explicit representation. Acknowledging the lack of information and
436 the difficulty to obtain it exhaustively, statistical representations and aggregate representations
437 are considered as pragmatical solutions and used in most modelling studies.

438 **5. How to obtain access to the information needed on small reservoirs?**

439 *5.1. What type of data?*

440 Stream discharge time series, at one or several points in the catchment, are required data
441 in statistical analyses (Section 4.1.2) and in the TEDI and Deitch models (Nathan et al., 2005;
442 Deitch et al., 2013, section 4.2.1), and such data are also used by the other types of models to
443 calibrate or assess the modelling. Such data are expected to be found in existing databases. Sta-
444 tistical analyses require rather long observation periods for both the discharge and the temporal
445 evolution of the reservoir network to cover contrasted periods. The modelling approaches gen-
446 erally need to collect more data, even if focusing on a shorter time period. These data include
447 atmospheric and physiographic data, as well as the characteristics of each reservoir (or of the
448 aggregated ones), the connection between the reservoirs, and the management of the reservoirs,
449 particularly in terms of abstraction. Table 2 presents some of the most commonly required data
450 on the reservoirs used for such studies.

451 *5.2. Physical and topographical characteristics of small reservoirs*

452 Data on small reservoir characteristics may be collected and stored in databases by stake-
453 holders or state or regional agencies. Although they are often a first base to initiate a study and
454 may prove very useful, such databases are generally incomplete, even for the census of the reser-
455 voirs, either because the survey did not include all the existing reservoirs or because the database
456 is not up to date. Moreover, all the needed data are not available. Therefore, to fill the gaps,
457 several methods can be used: i) additional field surveys, ii) remote sensing data (either satellite
458 or aerial images) and related image analysis techniques and iii) empirical relationships to recover
459 one variable according to other properties. In most studies, several methods are combined.

460 Here, only some indications on the available methods are presented because it is beyond
461 the scope of the present review to fully describe such techniques. Some details can be found

Variables	Description	Spatial representation	Access
Number	<i>number of reservoirs in catchment</i>	D/C/S/A	DB/RS/Map
Location	<i>geographical coordinates</i>	D/C	DB/RS/Map
River flows	<i>observed discharge at some places of the area under study (m^3/s)</i>	D/C/S/A	DB
Maximum area	<i>area of the free surface water (m^2)</i>	D/C/S/A	DB/RS/Map
Drainage area	<i>upstream basin whose runoff may feed the reservoir(s)</i>	D/C/S/A	DB/ER
Storage capacity	<i>maximum capacity volume of the reservoir(s) (m^3)</i>	D/C/S/A	DB/RS/ER
Abstraction	<i>volume and timing of water uptake in the reservoir(s) ($m^3/period$)</i>	D/C/S	DB/ER
River connection	<i>hillslope, across the river course, in diversion</i>	D/S	DB/RS/Map
Bathymetry	<i>relations between height-water volume-water free water surface area (m)</i>	D/S	DB/RS/ER
Age	<i>time since building the reservoir (year)</i>	D/S	DB/RS/Map

Table 2: Key variables needed to conduct a cumulative impact study of small reservoirs from the most common (top) to the less used (bottom). Spatialization can be either D: distributed, S: statistical, C: catchment or A: aggregated (see Figure 6). Access to the variables can be from DB: databases, RS: remote sensing (satellite data, aerial images, lidar and so forth), Map: mapping, or ER: empirical relationships (see subsection below). Variables in brown are associated with the management of the reservoir discussed in Section 5.2, whereas the other ones are discussed in Section 5.3.

462 in Nathan et al. (2005); Lowe et al. (2005); Hughes and Mantel (2010); Malveira et al. (2012);
463 Nathan and Lowe (2012); Bartout et al. (2015); Fowler et al. (2015).

464 Field surveys are not often described in the literature because they are quite basic. However,
465 field surveys represent a guaranteed method to locate all the reservoirs on a catchment and to
466 ensure their type of connection to the river. However, this method is time consuming and cannot
467 be used on large areas. The detection of reservoirs is efficient with remote sensing methods based
468 on aerial or satellite images, which allows retrieving both the number and areas of the reservoirs
469 (Chao et al., 2008; Messenger et al., 2016). However, very small reservoirs (approximately $100m^2$)
470 are still difficult to detect, even with high-resolution aerial images (Carvajal et al., 2014).

471 Storage volume and bathymetry are more difficult to assess by remote sensing (Gal et al.,
472 2016), whereas uncertainty in the storage volume can lead to important error in impact studies
473 (Hughes and Mantel, 2010; Fowler et al., 2015). Thus, some empirical relationships are most
474 often used. Based on a geometrical analysis of a variety of reservoir shapes, Molle (1991) showed
475 that the relations between the reservoir surface and volume correspond to power laws. The
476 parameters of the laws vary in space, depending on the geomorphological context, but remain
477 generally constant within a given region (Thompson, 2012). Consequently, a common approach
478 is to fit the law parameters from a set of reference reservoirs. The law can then be applied to all
479 reservoirs in the catchment (Malveira et al., 2012; Hughes and Mantel, 2010).

480 The drainage area of the reservoirs can be derived from digital terrain models. However, this
481 requires having a precise position of the reservoirs to be able to connect them with the correct
482 river reaches to avoid error in the estimation of the upstream drainage area (Hughes and Mantel,
483 2010). Moreover, the determination of the type of connection between the reservoir and the river
484 is a key point for assessing how the reservoir is filled. For modelling approaches that are not
485 fully distributed, it is possible to use some relationship between the free surface water area (or
486 volume) and the drainage area of the reservoir. Linear (Habets et al., 2014; Nathan et al., 2005)
487 or non-linear (Fowler et al., 2015) relationships have been used. However, these relationships are
488 again often specific to the studied catchment and cannot be generalised to very different contexts.

489 5.3. *Water reservoir management characteristics*

490 Water reservoir management operations refer to how the volume is stored in the reservoir
491 and released from the reservoir either downstream, outflow, or withdrawn for some usage (most
492 often, agricultural use). The type of reservoir-stream connection is an important driver for such

493 management, as shown in Section 3.3. Information on the connection can be included in some
494 databases managed by stakeholders or regional agencies, particularly where legal regulations ex-
495 ist, for instance, to maintain a conservation flow. However, as stated previously, such databases
496 are often incomplete. Hughes and Mantel (2010) show that it is difficult to obtain this informa-
497 tion from remote sensing. Covering all the small reservoirs with a field survey is also difficult;
498 such information is thus likely to be incomplete. This is perhaps the reason why most existing
499 studies do not consider the ability to disconnect the small reservoirs from the stream network
500 or to maintain some minimum flow by some type of diversion canal or low-flow bypass. Some
501 exceptions are the works of Fowler et al. (2009) and Thompson (2012) that considered low-flow
502 bypasses and of Habets et al. (2014) that considered the possibility to disconnect the reservoirs
503 during part of the year (as if they were in diversion) to manage a filling period as required by
504 the regional regulation. However, a limitation is that in these cases, the management operations
505 were supposed to be homogeneous within the basin.

506 Water abstraction is the most sensitive information needed to infer the cumulative impacts
507 of small reservoirs on hydrology (Hughes and Mantel, 2010; Fowler et al., 2015). However, the
508 abstraction is rarely known, and at best, only an annual estimation of the abstracted water volume
509 is known. To retrieve the temporal evolution of the water abstraction, which of course varies from
510 year to year, several methods are used in the literature, either based on the estimation of the water
511 demand or on the water offer (i.e. the available water volume stored in the reservoirs).

512 Water demand approaches attempt to quantify the needs associated with irrigating crops and
513 watering livestock. Consumption for watering livestock is considered to be constant through-
514 out the year (Fowe et al., 2015), whereas irrigation is estimated according to the sub-seasonal
515 climate conditions. The water demand of the crop is often calculated on the basis of the crop
516 coefficient K_c , which varies over time, and potential evapotranspiration (PET) (Fernández et al.,
517 2007; Wisser et al., 2010; Biemans et al., 2011; Fowe et al., 2015).

518 Water offer approaches consider that the abstraction accounts for a given fraction of the total
519 reservoir capacity. This approach is mainly used in Australia (Nathan et al., 2005; Cetin et al.,
520 2009; Fowler et al., 2015). The fraction of the total storage can be obtained through surveys of
521 reservoir owners or occasionally by remote detection (Fowler et al., 2015) and is highly variable
522 depending on usage (irrigation vs. watering livestock) and region. Nathan and Lowe (2012)
523 refers to fractions ranging from 10% to 400%, which implies that the reservoir can be filled

524 several times within a year. Although rather simple, this method allows considering a seasonal
525 distribution of the abstraction according to known uses (Cetin et al., 2009). This method can
526 also be used when no information on the abstractions is available simply by assuming that the
527 abstraction volume is a given fraction of the storage capacity (Habets et al., 2014; Deitch et al.,
528 2013).

529 **6. Discussion**

530 *6.1. The uncertainty issue*

531 Regardless of the approach (exclusively data-based method or modelling approaches), stream
532 flow is a crucial variable in any reservoir impact estimation and may be a source of uncertainty
533 in cumulative impact estimation. The uncertainty arises from uncertain measurements of stream
534 flow, including the need to transpose data from neighbouring catchments, as well as from time
535 series that are too short. It can lead to incorrect conclusions in trend analysis within statisti-
536 cal analyses of time series (Section 4.1.2) and in comparisons of paired-catchment hydrology
537 (Section 4.1.3).

538 In modelling approaches, when catchment models are used to simulate inflow to reservoirs
539 and transfer of reservoir outflow to the outlet, uncertainties in cumulative impact simulations
540 derive from uncertainties classically associated with catchment hydrologic models, namely, the
541 model itself (structure and parameters) and the data used to calibrate and validate the model. An
542 extensive presentation and discussion of these sources of uncertainty are beyond the scope of
543 the present review and can be found elsewhere (see, for instance, Hingray et al. (2009)). When
544 observed discharge is used rather than hydrologic catchment models, as in Deitch's model, in
545 TEDI or in CHEAT, the simplifications performed to spatialize observed discharge as reservoir
546 inflow may result in strong errors in reservoir dynamics, in outflow simulation and thus in cu-
547 mulative impact estimation. The assumption used to aggregate reservoir outflow may also be
548 another source of uncertainty. To our knowledge, no sensitivity and uncertainty analyses of the
549 simplifications and assumptions have been performed.

550 How the reservoirs are accounted for in the models, together with how the hydrological
551 processes are estimated, are key components of the models. Incorrect representations may lead
552 to significant uncertainty in the estimation of cumulative impacts. Indeed, processes and factors
553 that affect reservoir water balance (Section 3.1) and thus cumulative impacts (Section 4.2) are

554 numerous. In the approaches for quantifying cumulative impacts, choices are made irrespective
555 of the key processes and their representation; seepage, for instance, is often neglected (Table
556 1). The reservoir network representations (Table 1) in models also vary from one approach to
557 another. The physical, topographic and management characteristics of reservoirs (Table 2) may
558 also have uncertainties due to a lack of information or measurement and survey errors. The
559 uncertainty in the estimation of cumulative impacts is thus a key issue.

560 A few modelling studies have addressed this issue by conducting sensitivity analyses (Ha-
561 bets et al., 2014; Hughes and Mantel, 2010; Malveira et al., 2012; Nathan et al., 2005). Although
562 incomplete, three preliminary results can be emphasized. a) The effect of the uncertainty on the
563 estimated upstream drainage area of reservoirs on inflow is controversial. On the one hand, it
564 was shown to be a key morphological characteristic. This would have to be expected as the larger
565 the upstream drainage area is, the larger the flow intercepted by reservoirs (Habets et al., 2014;
566 Hughes and Mantel, 2010). On the other hand, the stream flow was shown to not be very sensi-
567 tive to the reservoir drainage area (Nathan et al., 2005). The hydrologic characteristics (annual
568 flow, monthly flow, and flow duration curves) taken into consideration to evaluate the cumulative
569 impacts may explain the differences between these findings. b) Water management of reservoirs
570 appears to play a dominant role in stream flow reduction. This was clearly shown by Hughes and
571 Mantel, quantifying the key role of water demand uncertainty confirmed by Güntner et al. (2004),
572 stating that "*local experience suggests that uncertainty in human withdrawal add the largest un-*
573 *certainty*". c) Nathan et al. (2005) found that for the studied Australian catchments, the spatial
574 representation of reservoirs, especially the topology and the cascading between reservoirs, does
575 not exert a great role on stream flow reduction within the range of reservoir distribution.

576 From these preliminary conclusions, we highlight in the two following sections the need and
577 the ways to improve knowledge of reservoir characteristics and estimate water abstraction from
578 reservoirs. Uncertainty derived from process representations also deserves a thorough analysis,
579 particularly how reservoir evaporation is quantified and the consequence of neglecting seepage
580 in most of the approaches. It is expected that the sensitivity and uncertainty propagation may be
581 different as functions of the hydrologic characteristics used to assess the cumulative impacts.

582 *6.2. Improving knowledge of small reservoir characteristics*

583 Estimating the cumulative impacts of small reservoir networks requires obtaining the key
584 physical and geometrical characteristics of networks and reservoirs (Table 2). Unlike large reser-

585 voirs, the knowledge of the characteristics constitutes a real and specific challenge in consider-
586 ation of the large number of small reservoirs within a catchment, up to nearly $10 / km^2$ in some
587 regions (Figure 2). This review shows that a variety of methods, ranging from field surveys to
588 remote sensing, are available. However, uncertainty in the estimation of characteristics can be
589 large and constitutes a difficulty specific to small reservoirs. One way to address this challenge
590 is to choose methods for impact estimation that are minimally sensitive to the lack of informa-
591 tion or uncertainty in small reservoir properties. This choice is made, for instance, in the global
592 and statistical representations of reservoir networks used in some modelling approaches. Global
593 indicators, as we investigated in this review, are also a way to overcome a lack of or uncertainty
594 in information about the key characteristics of small reservoirs. However, the development of
595 remote sensing methods and image analysis techniques should help in the future to map and
596 quantify the properties over vast areas while reducing the uncertainties (Zhang et al., 2012). Fol-
597 lowing this approach, remote sensing may also be a way to derive height-surface area-volume
598 relations (Mialhe et al., 2008). To date, such relationships established in a given region were used
599 for all the reservoirs, while relations may vary from one reservoir to another. The synthesis by
600 Carlier et al. (2016) found that operational studies collect a wealth of data on small dam network
601 properties, data that were rarely used beyond the studies. Therefore, along with improvements
602 in survey and remote sensing methods, one track to improve our capability of estimating small
603 reservoir cumulative impacts also relies on storing and sharing information collected through
604 operational surveys and scientific studies.

605 *6.3. Improving abstraction estimations*

606 When small reservoirs are intended to provide water for agricultural uses (irrigating crops
607 and watering livestock), abstraction is a key parameter in hydrologic reservoir dynamics and in
608 cumulative impacts (Hughes and Mantel, 2010; Nathan and Lowe, 2012). However, the present
609 review shows that current estimations rely on very pragmatic choices and simple methods be-
610 cause existing, readily available information about abstraction is very difficult to obtain in every
611 country. Water abstraction may vary broadly from one reservoir to another. Abstraction rate and
612 timing from a given reservoir result from a complex process including biophysical considera-
613 tions: crop or livestock demands, availability of reservoir water and also of other water resources
614 (river and groundwater). Social and economic considerations are also at stake: water abstraction
615 resulting from an agronomic strategy developed by farmers, involving crop yield and profit tar-

616 gets, also related to water resource sharing between water users. Abstractions at least depend on
617 laws or regulations fixing water use restrictions and downstream water release rates and timings
618 from reservoirs for other water functions.

619 Two ways may enhance abstraction estimations. In many countries, farmers have to declare
620 to water management agencies or state services the abstraction volumes and occasionally the
621 timing from their own reservoirs. Storing this information through database systems and making
622 it available would allow obtaining a precise estimation of where and when water is withdrawn
623 from reservoirs. Empirical relations relating the characteristics of reservoirs with crop or animal
624 needs could be one way to estimate and spatialize the water abstraction from small reservoirs
625 more accurately than the current simple and pragmatic methods. Another way would be to take
626 advantage of the agronomic state of the art in terms of crop management strategies. Decision rule
627 models are available to simulate and predict tillage, sowing, fertilization, hoeing, irrigation, crop
628 protection, and harvesting periods. Such models could be coupled to hydrologic models, allow-
629 ing estimating the impacts of agricultural land use strategy in a reservoir-equipped catchment on
630 stream flow and other water compartments. As an example, the MAELIA platform proposes a
631 framework to couple such crop models and decisional models with the SWAT hydrologic model
632 (Thérond et al., 2014).

633 *6.4. Impact indicators*

634 Simple indicators of cumulative impacts are needed by stakeholders and water management
635 actors. The challenge is the design of the reservoir system and particularly the identification of
636 sensitive areas where no other reservoir should be built, and even where some reservoirs should
637 be removed, while other areas could benefit from the construction of new reservoirs to increase
638 the available water resource. From a scientific perspective, this operational need consists of first
639 analysing whether cumulative impacts can be derived from properties of reservoir networks or
640 others. Our analysis shows that there is no relationship between the hydrological impact rates
641 and some simple network density indicator (Figure 2). The analysis was performed based on
642 data collected from worldwide studies involving a large range of hydrological, climatic, geo-
643 logical, pedological, and land use contexts. Catchment hydrological functioning, particularly
644 runoff temporal and spatial variability, must be a key factor in the impact process, although in-
645 dicators only based on reservoir properties do not account for. This point is clearly supported
646 by the variability of impacts for a given catchment depending on wet and dry years (Figure 1).

647 Furthermore, reservoir management (abstraction rate and time, outflow by water release, includ-
648 ing minimal outflow when relevant and connection to the stream) is also another key factor in
649 the impacts. The large number of factors involved in the cumulative impacts makes the search
650 for a universal indicator a never-ending quest. Instead, one research track would be to develop
651 regional indicators based on regional analysis of the cumulative impacts. Within areas of homo-
652 geneous hydrology, soil occupation, and standardized water management operations, indicators
653 of reservoir network properties may be more relevant than at the global scale. Following this
654 approach, Hughes and Mantel (2010) proposed and explored for a few catchments the relevancy
655 of an indicator integrating the annual water demand for small reservoirs, a measure of stream
656 flow temporal variability and the mean contributing area of reservoirs. They found a correlation
657 between the indicator and the annual mean flow decrease. Another important point would also be
658 to differentiate between exploited and non-exploited reservoirs, considering the role of reservoir
659 management on the impacts.

660 **7. Conclusion**

661 In this study, we investigated the cumulative impacts of small reservoirs on water resources
662 from a quantitative aspect only. Although the reviewed studies agree that the main impacts of
663 small reservoirs are a decrease in the river discharges and peak flow due to water abstraction
664 from the reservoirs and water losses, the intensity of this decrease can vary considerably and is
665 not easy to anticipate with various types of indicators. Impacts on low flow and river regime
666 can vary from basin to basin due to the many types of reservoirs and their different uses. It was
667 shown that a key issue with studying the cumulative impacts of small reservoirs is the lack of
668 data on the properties and usage of the small reservoirs, which leads the various studies to adapt
669 their strategy to address this ill-defined problem by using assumptions to simplify the estimation
670 of these characteristics.

671 However, this review focused only on some aspects of the impacts of small reservoirs. Indeed,
672 the numerous small reservoirs also impact sediment transfer, hydromorphology, biodiversity, and
673 biochemistry. Although the literature on such topics associated with small reservoirs is not vast,
674 these aspects were reviewed by Carlier et al. (2016). From this review, it appears that a fine
675 spatial and temporal estimation of the hydrological impact may be required to assess these other
676 impacts. The lack of data on some characteristics of the small reservoirs is also challenging. Even

677 with such difficulties, it is assumed that small reservoirs have a large impact on sediment trapping
678 (Yang et al., 2011) and river channel (Petts and Gurnell, 2005). The impacts on some biochemical
679 components can accumulate according to the discontinuity distance (Bergkamp et al., 2000). The
680 impacts on biodiversity (especially fishes) from large reservoirs are rather well known (Poff and
681 Zimmerman, 2010); thus, the question is now how to reduce the major impacts by removing the
682 most impacting reservoirs (Poff and Hart, 2002; Doyle et al., 2005; Grantham et al., 2014). There
683 is no doubt that the question of removing small reservoirs should also be extended to attempt to
684 reduce the other types of impacts, including quantitative hydrological impacts.

685 Socioeconomic impacts are also very important to consider since it is often the key driver
686 to build reservoirs. It was shown in India that large reservoirs can have some drawbacks for
687 the neighbouring population (Duflo and Pande, 2007). However, this impact can be reduced
688 by the presence of small reservoirs that are having positive socioeconomic impacts on the local
689 population (Blanc and Strobl, 2013; Acheampong et al., 2014). Lasage et al. (2015), for instance,
690 focus on the social benefit of small sand reservoirs to secure water access in the context of climate
691 change.

692 Indeed, it is rather important to consider the long-lasting life of the reservoir (more than 50
693 years) since this means an impact in the long term, but also within a changing climate. As stated
694 in the introduction, there is increasing pressure to build reservoirs, partly to adapt to climate
695 change. The global impacts of small reservoirs on hydrology are already estimated to be 5%
696 of the mean discharge and 44% of the low flow (Wisser et al., 2010), although the impacts can
697 vary in space and season (Wanders and Wada, 2015). Moreover, there is an increasing number
698 of studies that show that water management can aggravate the duration of droughts, particularly
699 where the development of water use was not controlled and for longer droughts (Van Loon et al.,
700 2016; He et al., 2017; Lin et al., 2017). It is thus important to integrate in new projects the
701 cumulative impacts of the reservoir network in the basin, as well as its ability to evolve in time
702 according to the hydrologic conditions due to global change.

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Table A.1:

707 now AFB (French Agency of Biodiversity), and conducted by Irstea, in partnership with INRA.
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714 **AppendixA.**

Ref	Basin	A	LU	Dam	P	PET	Q	VD	ND	M	Impact
CHECK DAMS											
Martinez Alvarez et al. (2007)	ESP, Sierra Gador	320	Low vegetation	CD	400	900	9.3	0.6	0.3	A	Increase groundwater recharge
Xu et al. (2013)	CHN, Yanhe	7 725	Grassland	CD	505				0.8	OBS natm	-14.3% AD + erosion impact
FLOOD CONTROL DAMS											
Ayalew et al. (2017)	USA, Soap Ck	660		FL,FI,LS,FP				62	0.2	D	Reduce peak flow by 20% to 70%
Frickel (1972)	USA, Willow Ck	1 400	Grazing, conservation, farming	FL	320			42	0.1	Obs	-18% AD + reduction of peak discharge
Kennon (1966)	USA, Sandstone Ck	221	3/4 grassland, 1/4 cropland	FL,LS	635		76	120	0.1	Obs	-12% AD
Ramireddygari et al. (2000)	USA, Wet Walnut Ck	4 100	65% cropland	FL, I	510		108			A	Decrease in runoff and piezometric level
FARM DAM: a) Approaches based on observations											
Carvajal et al. (2014)	ESP, Almería	7		I	250			68	39.5	WB	Collecting rainwater from the roofs of the greenhouses and covering small dams could reduce external water needs by 53%.
Martinez Alvarez et al. (2008)	ESP, Segura	3 774		I		1850	170	78	3.7	WB	Regional evaporation losses of small dams represents 27% of the domestic water use in a 2 million inhabitants region
Culler (1961)	USA, Cheyenne	23 569	Grazing, sagebrush	LS	366		4	3.2	0.4	Obs	-26% AD
Dubreuil and Girard (1973)	BRA, Sitia	1 790		I	700	2 100	72	34		Obs	-11% to -24% AD
Galea et al. (2005)	FRA, Séoune	463		I				14	0.3	Obs stat	Winter flow reduced by 31%
	FRA, Tescou	287		I				15	0.6	Obs stat	Winter flow reduced by 42%
Schreider et al. (2002)	AUS, Yass R.	388		I,LS			53.1	17	5.8		-9.5% AD ; 1MI increase in farm dam storage corresponded to a 2 to 3 MI decrease in streamflow annual yield
	AUS, Broadwater CK	108		I,LS			55.5	33	3.5		-8.3% AD
Thompson (2012)	NZL, upper Tupiko R	0.7		LS	656.5	653	216	16.6	4.3	Obs Pair	-40% AD + change in flow regime

Table A.1 continue on next page

FARM DAMS: b) Approaches based on aggregated model											
Hughes and Mantel (2010)	ZAF, H10A Bread R.	234	Deciduous fruit orchards	I,LS	500 to 1 000	1 650	154	0.1	0.6	A	-17% AD
	ZAF, H10B Bread R	162	Deciduous fruit orchards	I,LS			273	0.1	0.5	A	-21.5% AD
	ZAF, H10C Bread R	260	Deciduous fruit orchards	I,LS			564	0.1	0.8	A	-27% AD
	ZAF, H10D Bread R	97	Deciduous fruit orchards	I,LS			2 054			A	18% AD
	ZAF, X21F	397	Stock grazing	I,LS	760	1 400	109	0.02	0.5	A	-16% AD
	ZAF, D52A	378	Stock grazing	I,LS	320	1 900	13	0.02	0.1	A	-35%
Perrin et al. (2012)	IND, Gawel	84	Semi-arid scrubland, rainfed crop, irrigated rice	I	812	1 800				A	Evaporation loss is dominant. Tank infiltration represents 43% of the groundwater recharge on average, 54% AD during dry year and 32% AD during wet year
Tarboton and Schulze (1991)	ZAF, Midmar	912			952		110			A	-6% AD
Habets et al. (2014)	FRA, Layon	930	Maize, vineyards	I	660		1 475	1.5	1.4	Ag	-9% AD
Meigh (1995)	BWA, Garo-bone	3 983		I,DW	500	2 000	7.6	6.5	0.05	As	-25% AD
	BWA, Bokaa	3 570					3.7	1	0.03	As	-13% AD
	BWA, Shashe	3 650					29	0.04	0.004	As	-0.2% AD
O'Connor (2001)	ZAF, Limpopo R. Kolope-Setonki sub-basin	1 992	Riparian woodland		377	2050	3.5		0.04	Anat	The many small farm dams reduce flow during critical dry years to levels causing dieback of some vegetation
FARM DAMS: c) Approaches based on statistical model											
Cetin et al. (2009)	AUS, Campase R.	4 000		LS, I		1 350	74.	11	3.2	S	7%
Fowlert et al. (2015)	AUS, Stringybark Ck	73			1 050		116	43.2	7.7	S	-22% AD
Güntner et al. (2004)	BRA, Upper Jaguaribe	24 200	Woodland, cattle farming crops (bean, maize)	I	700	2 300	285		0.2	S	-21% AD
Nathan et al. (2005)	AUS, Avoca R.	77	Grazing	I,LS	580		70	6.7	2.8	S \	The natural flow is closed to the observed one and there is small

Table A.1 continue on next page

											differences between distributed and statistical modelings
	AUS, Woollen Creek	11	Grazing and broad-acre crops	I,LS	930		66	40.1	10.8	S	The natural flow is underestimated by the statistical model compared to the distributed model, which lead to underestimation of the impact of small dams by a factor of 2.
	AUS, Lenswood creek	28	Agriculture dairy production		1 030		230	36.8	7.9	S	
Neal et al. (2000)	AUS, Ten Mile Ck	46		I,LS			178			S	-0.7% AD
	AUS, Arthuies Ck	105					96			S	-3.1% AD
	AUS, Mont Cole Ck	158					102			S	-4.8% AD
	AUS, Running Ck	126					291			S	-0.6% AD
	AUS, Woori Yallock Ck	322					293			S	-1.5% AD
Malveira et al. (2012)	BRA, Upper Jaguaribe	24200		I,DW	700	2 300	66	589.2	0.16	S	
Teoh (2003)	AUS, Onkaparinga	560			770	1 560	134	15	4.8	S	-8% AD
Thompson (2012)	NZL, upper Tupiko	85		LS,I	1 428	653	568	8	5.3	S	-1.1% AD
	NZL, upper Tukituki	740			849	653	6 450	6.5	2.9	S	-0.9% AD
FARM DAMS: d) Approaches based on distributed model											
Deitch et al. (2013)	USA, Russian R.	743	Mostly vineyard					6.7	0.6	D	More than 25% of the drainage network below reservoirs is impaired by over 50%. Impacts are more important for early season flow and upstream basin
Shinogi et al. (1998)	LKA, Tirrapane	10		I	1 491	2 445				D	Irrigation is 11% of inflow, seepage and evaporation losses 28.5%

Table A.1 Some insights on the references that address the cumulative impacts of small dams on water resources: Ref: references; Basin: country code and name of the basin; A: area of the basin in km²; LU: land use; Dam: type of dam; P: mean annual precipitation (mm/year); PET: mean annual potential evapotranspiration (mm/year); Q: mean annual river flow (mm/year); VD: volume density of the dams in 1000 m³/km²; ND: density of dams expressed as number per square kilometre; M: method used for the study; Impact: reported impact. Abbreviations for methods: A: Aggregated modelisation; Ag: aggregated on grid; As: aggregated on sub-catchment; D: distributed modelisation; S: statistical modelisation; OBS: direct observation; OBS&nat m: observation of river flow associated with natural modelling (without dams); WB: water balance approach; OBS stat: statistical analysis of observed river flow; OBS Pair: pair catchment experiment; Abbreviations for dam use: CD: check dam (erosion); FI: fire protection; FL: flood control; FP: fish pond; LS: livestock; I: irrigation; DW: drinking water; Abbreviation for impact: AD: annual discharge

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